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Title: Linear Induction Accelerator Cell Voltage Calibration Using Compact Electron Permanent Magnet Spectrometer

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Linear Induction Accelerator Cell Voltage Calibration Using Compact Electron Permanent Magnet Spectrometer

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Introduction

The Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility provides flash radiography capabilities using electron Linear Induction Accelerators (LIA's). The strict requirements for flash radiography require a detailed understanding of the LIA's performance, including precision measurements of the electron beam energy. Axis-1 of DARHT produces a 20 MeV, 2 kA, 80-ns-FWHM electron beam. Electronic measurement with cell-voltage monitors which consists of a 75 ohm load resistor and a current viewing resistor (CVR) that are coupled together and injector capacitive monitors (EVACSUM) are summed to give the total beam energy at the output of the accelerator. Calibration of these monitors was last done in 1999 and is needed. Using the Compact electron Permanent Magnet Spectrometer (CePMSpec), we have developed a technique for measuring and adjusting the calibration of the accelerator cell load resistor/CVR by using the total energy of the beam. Each pair of cells is driven by pulsed power Blumleins, and each Blumlein is charged by a Blumlein Charge Unit (BCU). There are 64 cells and 32 Blumleins and BCUs. This technique is applied to all 32 BCUs.

Spectrometer Description

Figure 1 shows a 3D drawing of CePMSpec [Ref 1]. It consists of a collimator at the electron beam entrance, a vacuum chamber for beam transport and a removable 60-degree sector magnet constructed by SABR Enterprises [Ref 2] that is used to analyze the momentum of the incoming electron beam. There are electron detection planes located on the straight-through port and on the 60-degree ports. The planes are designed to accept phosphor screens or GAF Chromic film for time integrated measurements. The screen/film can be replaced by scintillators for time-resolved measurements using gated or streak cameras. The length of the spectrometer along the beamline without the collimator is about 400 mm (16"). The spectrometer requires no power supply with controls for cycling or cooling for the magnet. The entire assembly, with magnet installed, weighs about 35 kg (75 lbs).

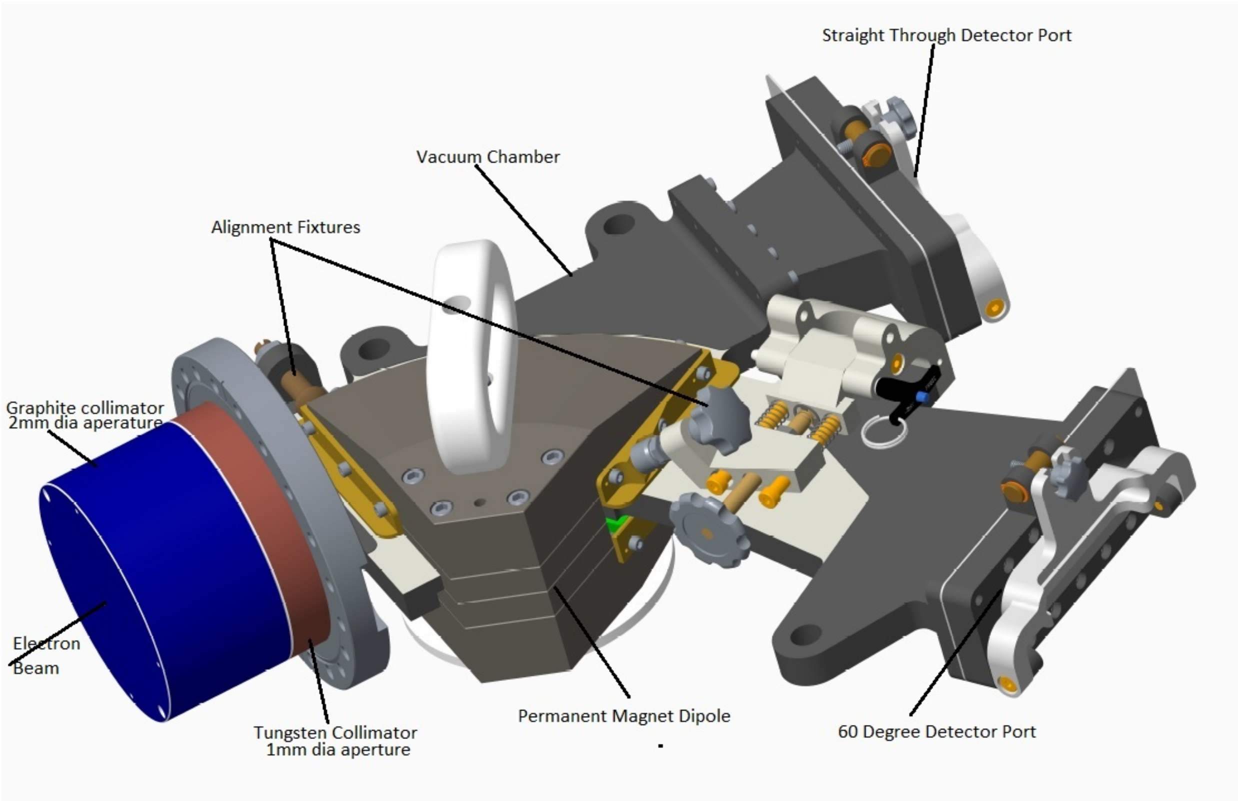


Figure 1. Schematic of CePMSpec.

Figure 2 depicts central and extreme trajectories through the spectrometer for various electron energies. The chamber accommodates a +/-50-mm-wide detection field relative to the center trajectory. Trajectories with larger momentum (energy) are bent the least. The 20MeV magnet was used for this experiment

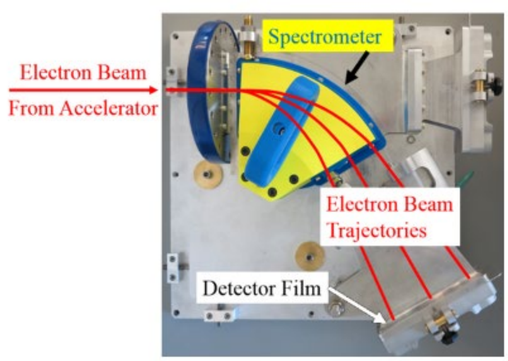


Figure 2. Spectrometer trajectories for multiple energies

Since the permanent magnet mounts to the vacuum chamber using its upstream edge as reference, the magnet can be adjusted to various positions to slightly increase or decrease the central energy thereby changing the range of available energies. Figure 3 shows the effect of changing the location of the permanent magnet on the electron trajectory. A small inward change in radius, r, produces a longer path length or trajectory in the magnet (magnetic field), therefore, the same energy trajectory is bent more. The 20 MeV permanent magnet was used with 15mm offset [Ref 1].

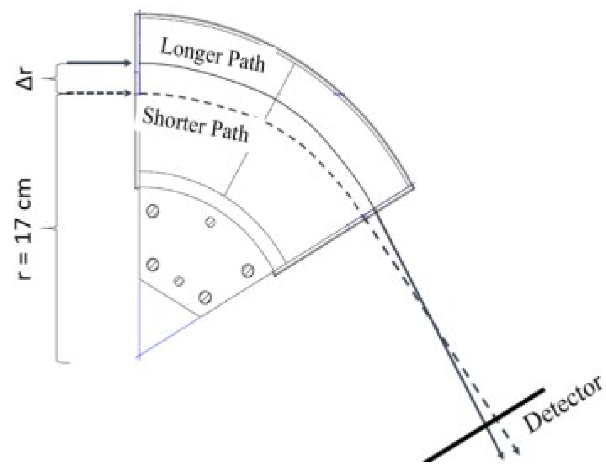


Figure 3. Trajectories for offset magnet

Accelerator Configuration

The spectrometer is placed in the Axis 1 drift downstream of DT-1 and upstream of the beam stop (Figure 4). It is attached on axis to the output flange of diagnostic chamber which has been aligned to DT-1 with a laser tracker. The spectrometer 1-mm-diameter collimator is aligned to the beam axis by the flange. The envelope code XTR [Ref 3] is used adjust the upstream transport solenoids to produce a large diameter beam on the collimator. The accelerator beam envelope tune is shown in Figure 5. Solenoids in the last cell block and DT-1 are turned off. The collimated beam is shown in Figure 6 and is calculated to be 9 nC (150 mA for 60 ns) with a

355-A input beam from a 25-mm-diameter cathode. The BCU charge voltage was 25 kV except for BCU08 at 20 kV.

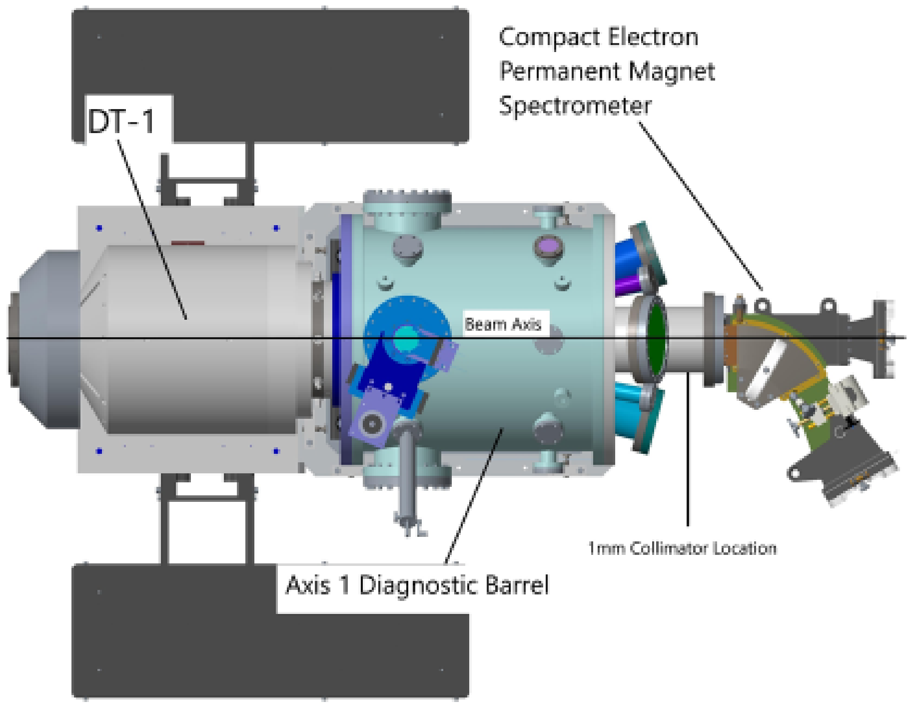


Figure 4. Schematic showing location of CePMSpec relative to Axis 1 DT-1 solenoid

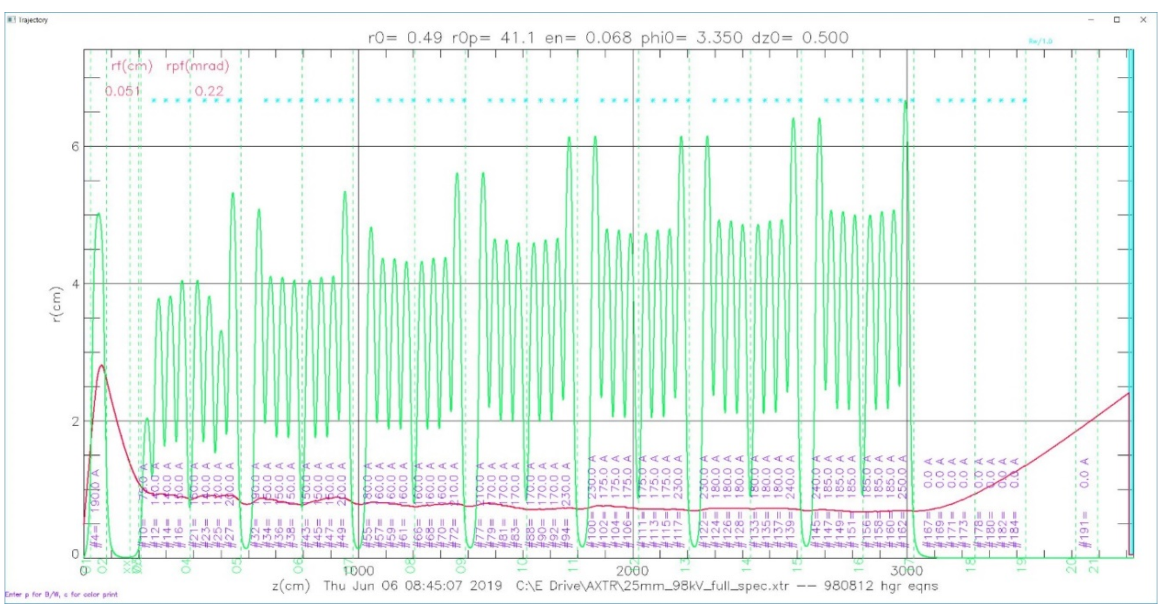


Figure 5. Beam envelope through the accelerator to the spectrometer collimator

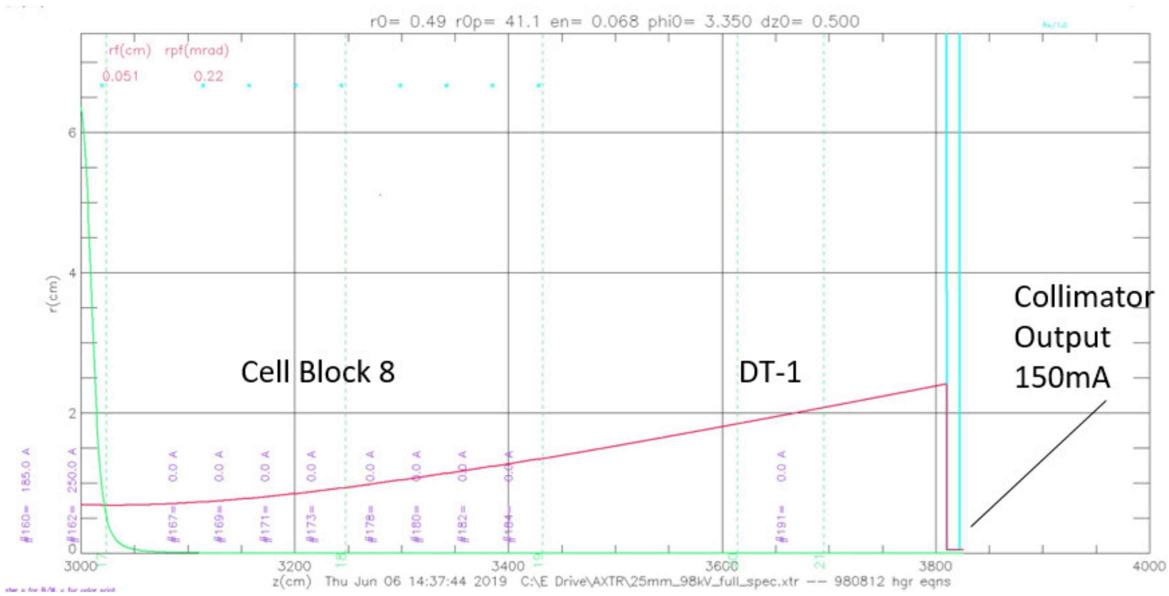


Figure 6. Collimated beam envelope.

Experimental Plan

DARHT Axis 1 has 32, Blumlein-Charge Units (BCUs).Each BCU drives 2-accelerator cells. Figures 7 and 8 are pictures of the BCUs and Cells on DARHT Axis 1. A GAF Chromic film inserted in the 60 degree detector plane of the spectrometer. The accelerator was pulsed once with all BCUs on and then again with one BCU off. The same film was exposed to both pulses. Each pulse can be distinguished on the film. This was performed for each of 32 BCUs. A total of 64 machine pulses were taken. Electronic CVR waveforms were recorded on digitizers for all of the 64-pulses. Using the existing calibration for the CVRs, the change in beam energy was determined and compared with the change in energy observed on the spectrometer. An average correction was determined for both CVR calibrations referenced to a single BCU such that the CVR data matched the mean spectrometer change in energy.

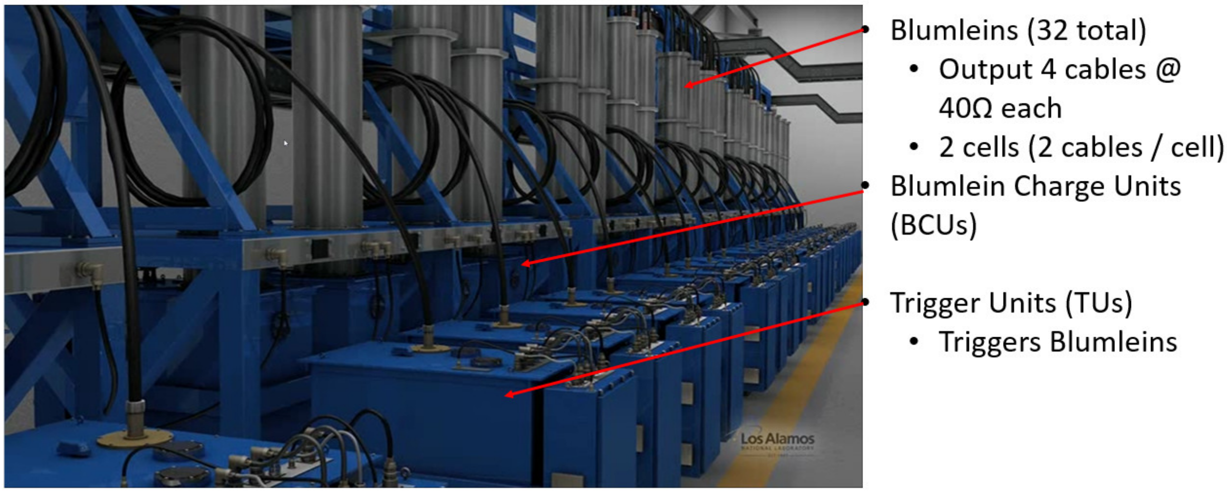


Figure 7. Blumlein layout in Axis 1 power supply hall

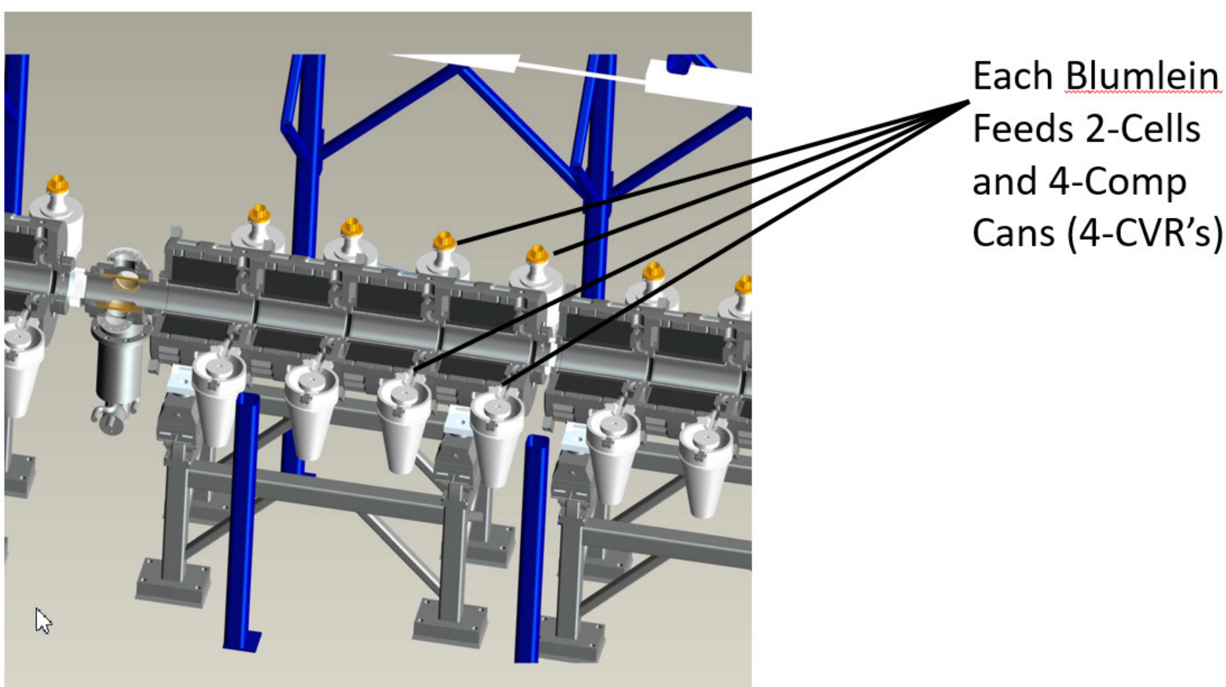


Figure 8. Comp cans and BCU feeds

Results for Single BCU

Centering of the beam is important for the accuracy of the spectrometer. The 1-mm-dia collimator is used to center the electron beam on the entrance to the spectrometer. This is verified by first removing the magnet then placing a GAF Chromic film on the 0 degree port (straight through detector port shown in Figure 1) located 373 mm from the exit of the tungsten collimator. The accelerator is pulsed and the location of the transmitted 1-mm-diameter beam from the collimator is recorded on film. Figure 9 (a) is an image of a GAF Chromic film that was scanned using Epson V850 Pro scanner with a 25 um square pixel scan size of the straight through film. Analysis shows [Figure 9 (b)] that the collimated beam is centered horizontally within 0.1 mm and vertically within 0.6 mm. BPM20 and BPM21 indicate a centroid beam angle striking the collimator 3 mrad. The acceptance of the fine tungsten collimation is 4 mrad. The asymmetry in the scanned GAF chromic data suggest possible scraping in the collimator. This result verifies that the beam alignment into the spectrometer is correct in the horizontal plane but is off slightly in the less important vertical plane.

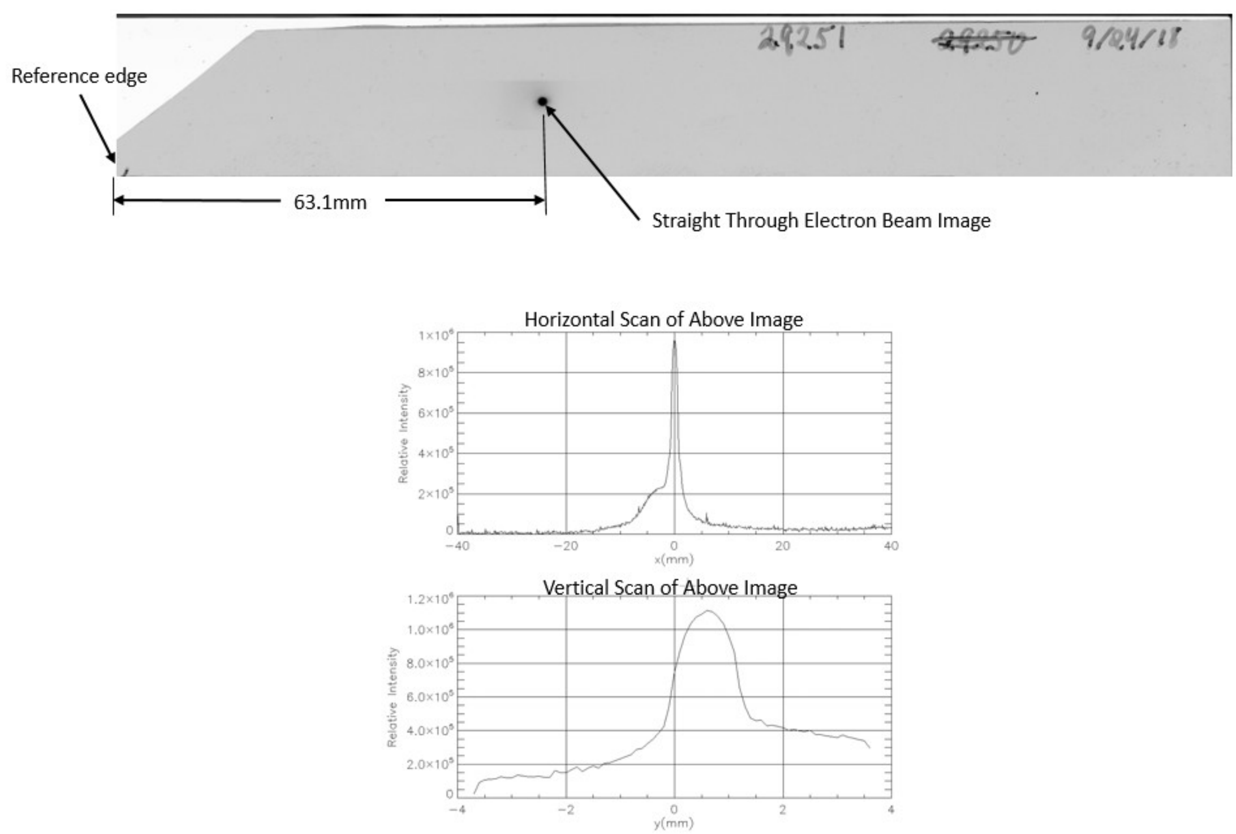


Figure 9. (a) GAF Chromic film image of straight through electron beam and (b) vertical and horizontal line outs.

Figure 10 is another image of a GAF Chromic film that was scanned using the same parameters as above. It shows the time-integrated beam distribution of the output of the permanent magnet spectrometer for BCU 30 OFF and full machine, BCU30 ON. The spectrometer magnet was positioned with a 15 mm offset (Ref. 1). The reference plane shown in Figure 10 is located 63.1+/-0.1 mm from the center of the spectrometer output. With the reference plane location, the data on the film relative to the center location on the spectrometer is accurately determined and the conversion from pixels to mm is accomplished. Figure 11(a) is a black 12 mm long line perpendicular to the reference plane with the red derivative overlay. The derivative is a common technique used for edge determination in an image. A zoomed in version is shown in figure 11(b). The location of the reference plane is chosen to be the peak of the derivative (pixel 2461 in this case). This calculation is performed for each GAF Chromic film for all 32 BCUs.

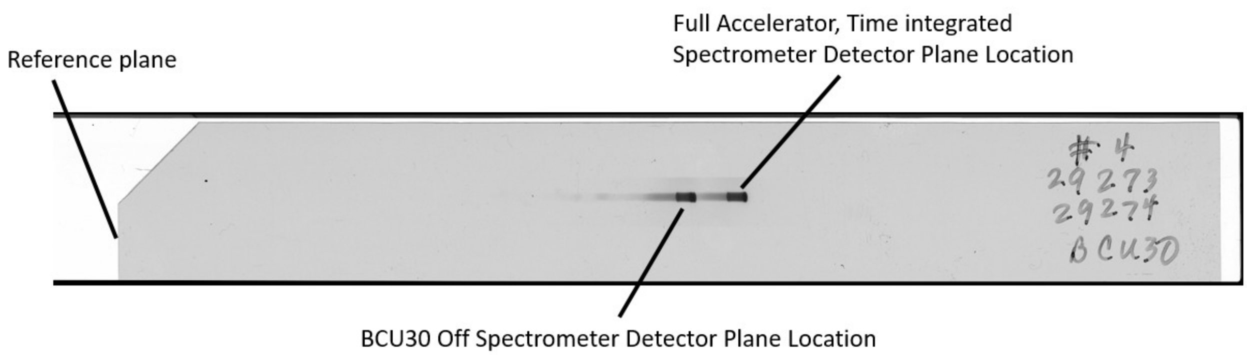


Figure 10. Electron beam image on GAF Chromic film inserted on 60 degree detector port.

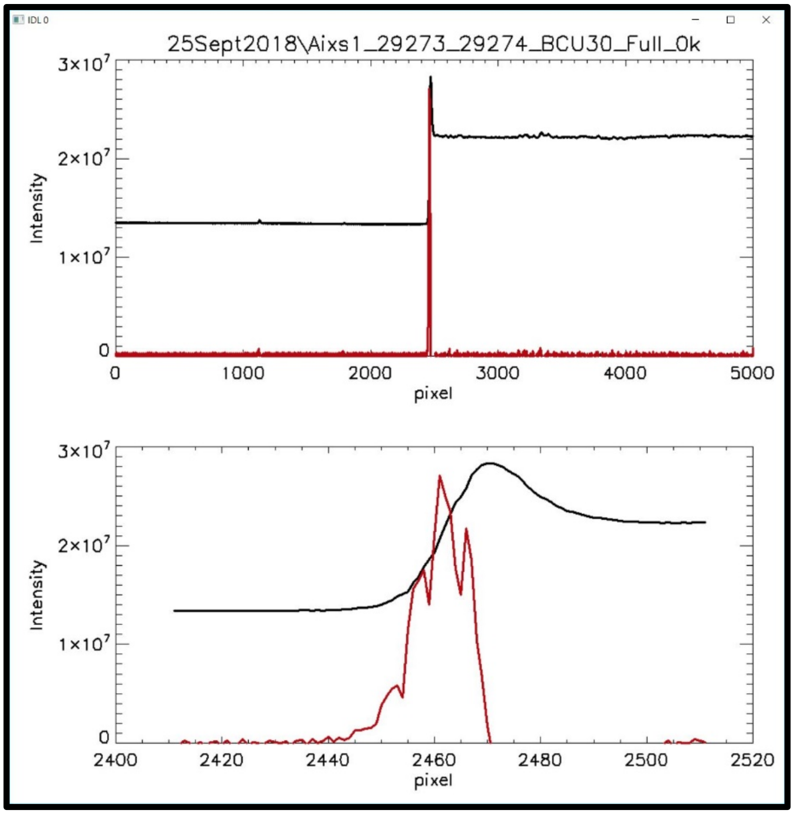


Figure 11. (a) Line scan through the reference plane and (b) same plot zoomed in to the reference edge

Figure 12 is a plot of vertically integrated image of Figure 10. The image data used is located below the graph. The scan shows two energy peaks corresponding to BCU30 ON and BCU30 OFF. The two highest peaks are selected by a background subtraction roughly the magnitude of the secondary peaks. This yields two well-defined distributions (Figure 13a and 13b). The mean of the peak of each distribution is calculated and converted to energy using the reference plane, mean location and the spectrometer calibration [Ref 1].

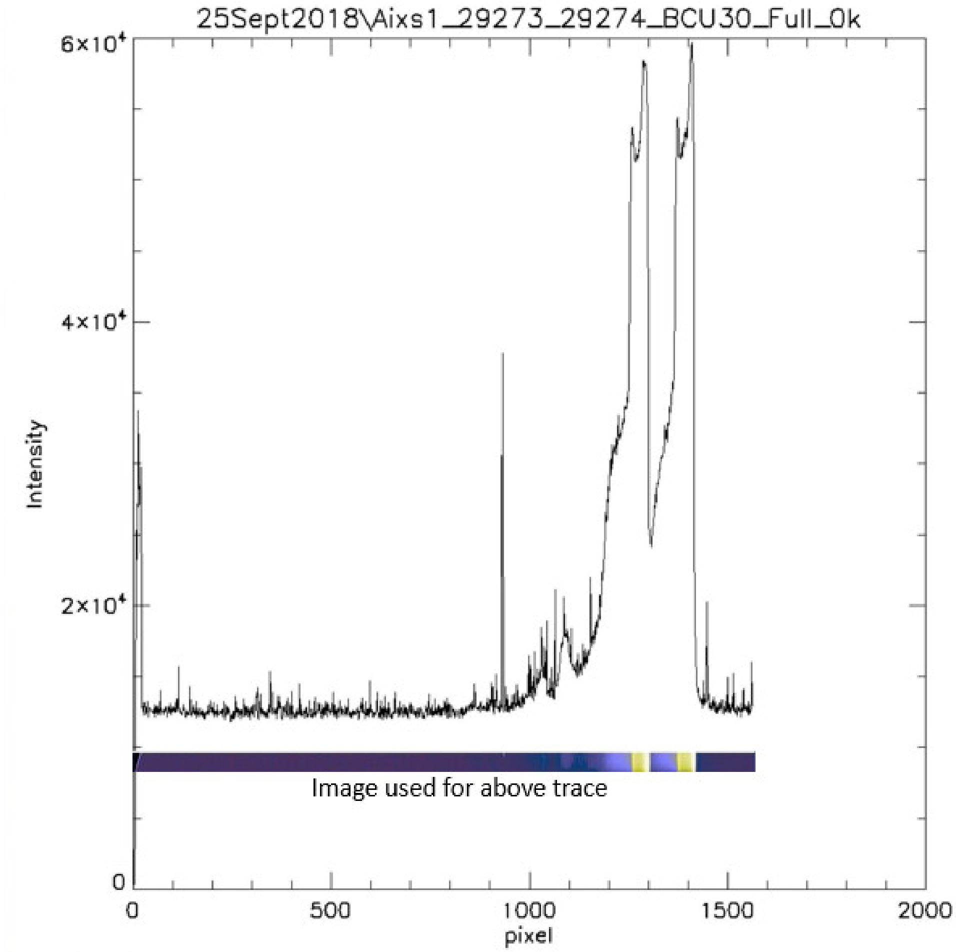


Figure 12. A line scan generated from vertically integrated compressed image located below the graph

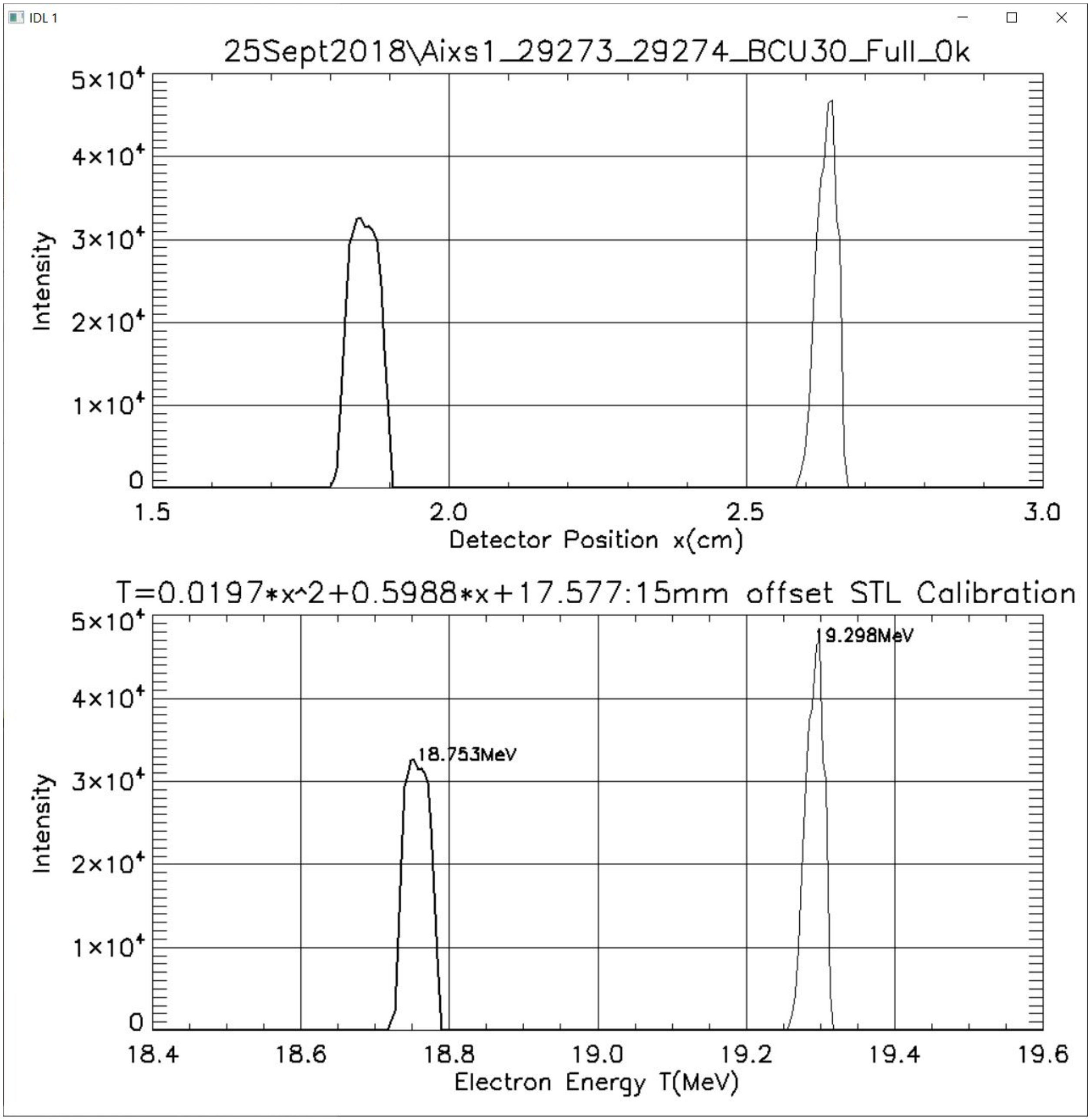


Figure 13. 13 (a) Result of line scan obtained by selecting only the peaks of the distribution in Figure 12 and (b) the same as (a) with the energy calibration factor applied[Ref 1]

Primary electronic monitoring of the Axis 1 cell is done at the compensation resistor (comp can). The comp can is shown in Figure 8. There is one comp can on each side of the cell. Each is fed by a separate HV cable coming from the BCU. There are a total of128 CVR's, one on each side of the 64-cells. The even numbered CVR's are the only ones monitored. The schematic of a single comp can is shown in Figure 14. The current viewing resistor (CVR) is at the base of the 75-Ω load resistor. The nominal resistance of all of the CVRs is approximately 0.75 mΩ. This yields a scope calibration of ~100kV/V.

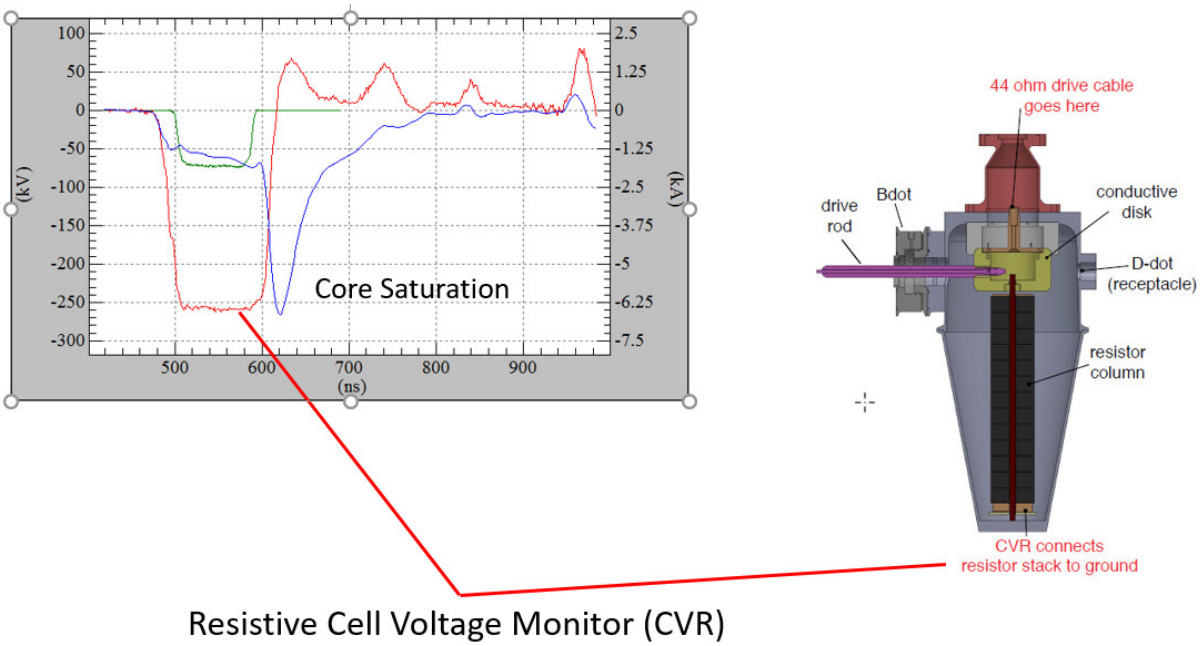


Figure 14. DARHT Axis 1 Compensation Resistor and CVR location

BCU30 feeds cells 59 and 60 and the associated CVRs are 118 and 120. Figure 15 is the summed waveforms for CVR118, 120 full accelerator voltage (blue) on the cells 59 and 60. Also shown in orange is the summed voltage on these cells with the BCU30 turned off. This voltage is positive since energy is extracted from the beam when there is no voltage applied to the cell. This is condition is also called "beam loading" because a non-driven cell loads the beam by reducing energy from it. The black arrow indicates the differenced value that is measured with the spectrometer.

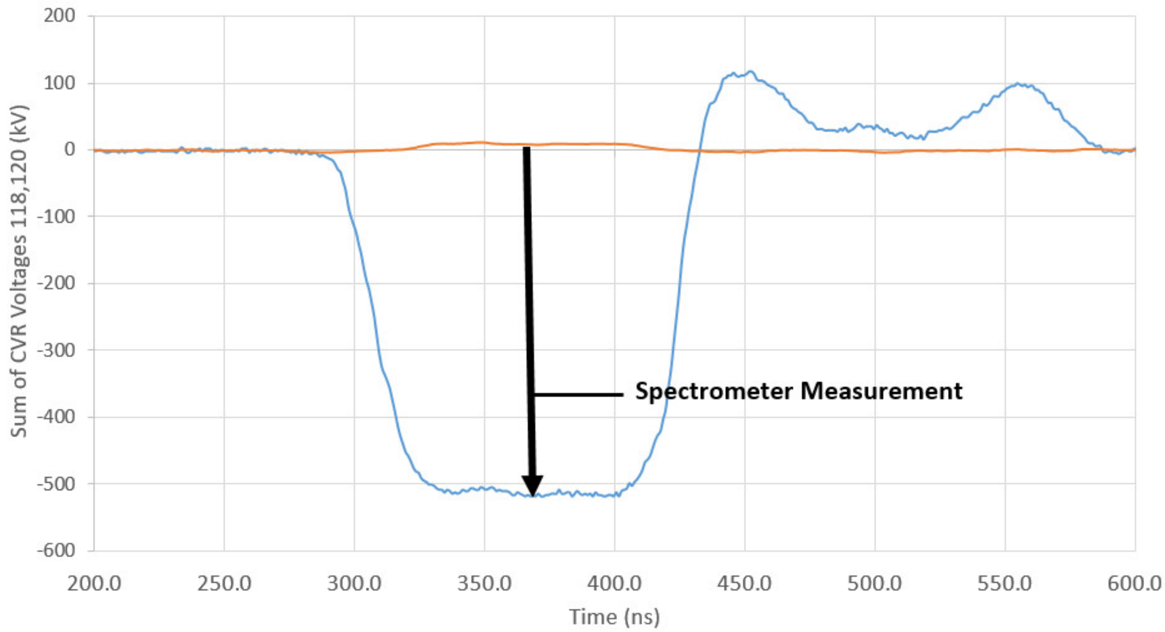


Figure 15. Comparison of spectrometer and CVR measurements

The individual waveforms for CVR 118,120 with the old calibration factors are shown in Figure 16. The waveforms are cut on the 60ns flat top of the signal. The waveforms are averaged, added together and then subtracted.

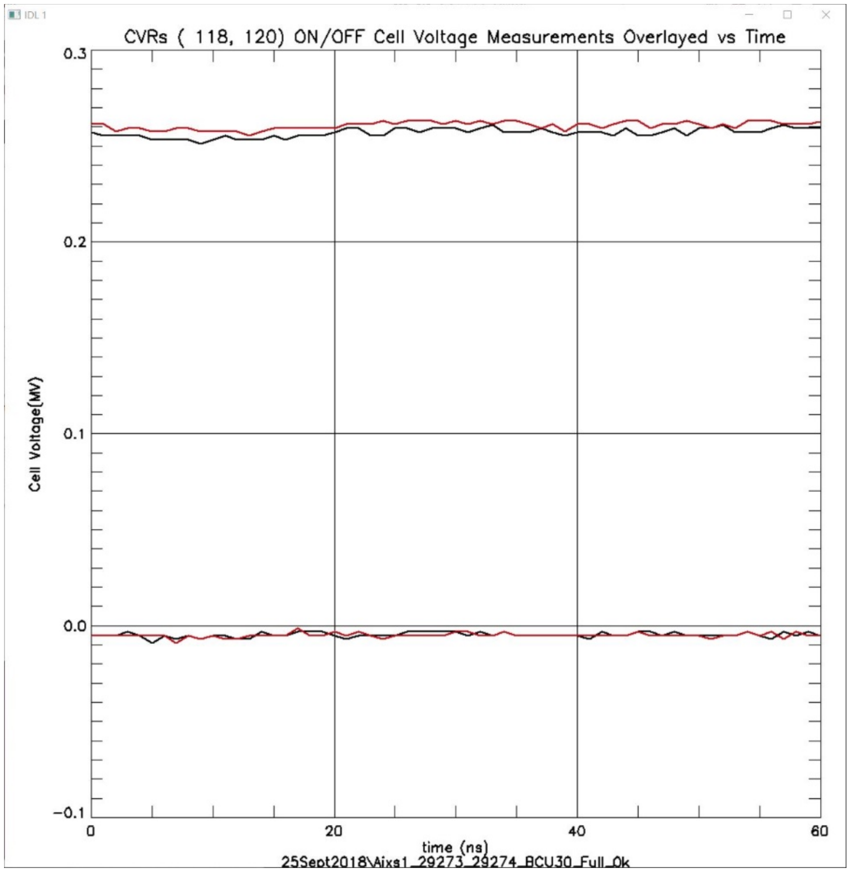


Figure 16. BCU 30 CVR measurements for ON an OFF. Note beamloading produces a slight opposite polarity for BCU OFF

The BCU30 ON accelerator and BCU30 OFF differenced result is shown for time-averaged CVR and single-point spectrometer data in Figure 17. By adjusting the CVR to match the spectrometer, we obtain a correction factor. The product of this factor and the old CVR calibration yields the new calibration factor. The correction factor is used for both CVRs on the two cells that are fed by BCU30. This calculation is done for all 32 BCUs. All of the spectrometer data were taken on a single day. The first data of the day was BCU32 (CVR128, 126) the last data was BCU01 (CVR002, 004).

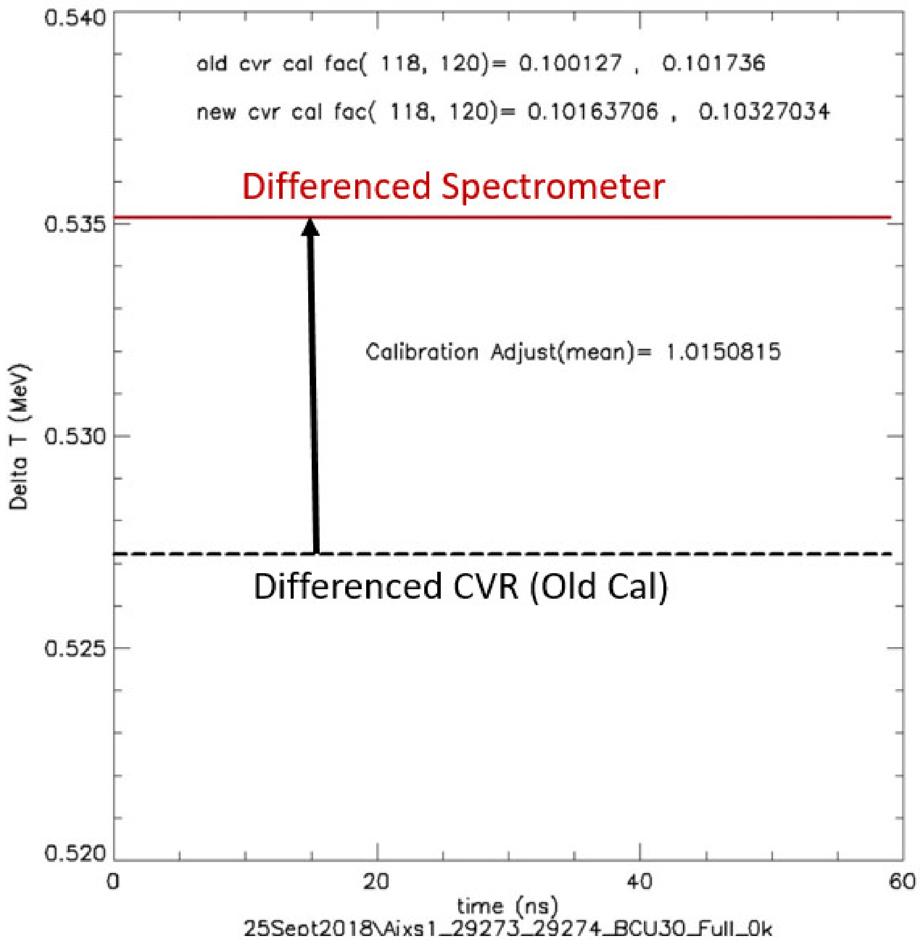
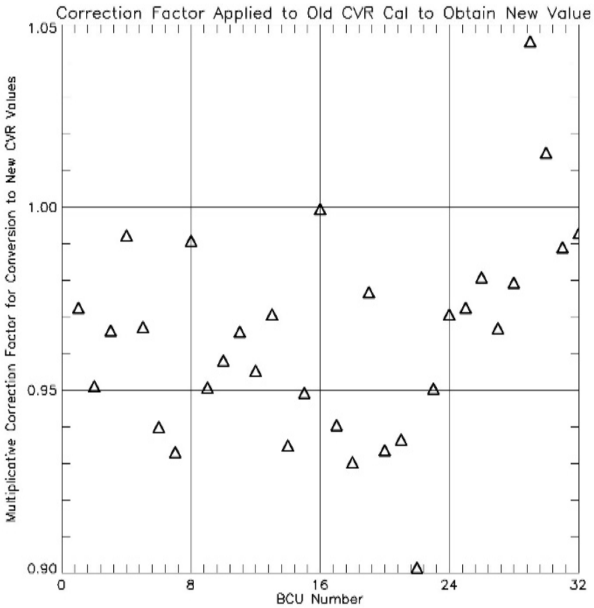


Figure 17. CVR correction referenced to the spectrometer

Summary and Conclusion for All BCU's

The Figure 18 calibration is done for all 32-BCUs and the correction factor is summarized in Figure 18 a). The resulting new calibration factors are shown in Figure 18 b) and are inserted into the waveform analysis code "wid_beam" for shot # 29273 and used to calculate the beam energy using cell voltage sum (16.09 MV) and injector voltage (3.38 MV) . The measured spectrometer voltage was 19.29 MeV. The result from the sum of the electronic measurements is 19.47 MV and agrees with the spectrometer to within 1%. The original CVR calibration gave a cell voltage sum of 16.58 MV compared with the new sum of 16.09MV, approximately 3% lower.



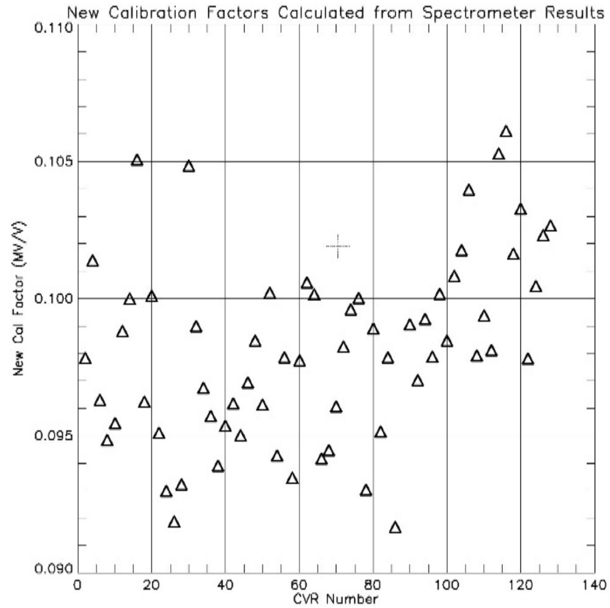


Figure 18. a) Correction factor summary for all BCUs and b) new CVR calibrations for all cells

An additional result of interest is shown in Figure 19. The plot shows the fluctuation in voltage delivered to the cells by all of the BCUs. Ideally, if all of the BCU/cells were identical, the difference voltage from the spectrometer would be constant. There is a +/- 4% fluctuation in the voltage supplied to the cells for all of the BCUs. Measurements of multiple BCUs into the same resistive load show very little variation in amplitude and shape (N. Kallas). This means that variation in voltage must come from the cell ferrite/load resistor variation from cell to cell.

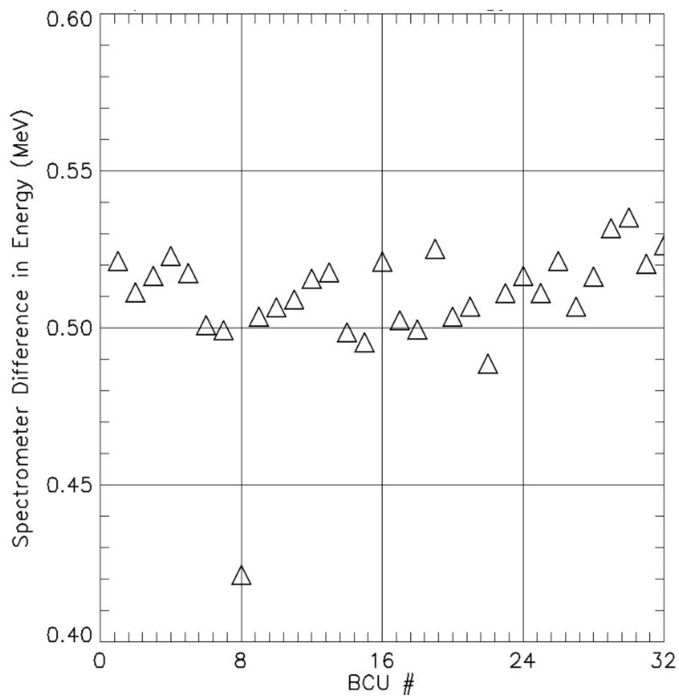


Figure 19. Fluctuation in electron beam energy caused by de-energizing individual BCU's

Finally, Figure 20 is a plot of the beam energy made as a function of BCU. The data were taken starting with BCU32 first and then unit by unit down to BCU01 during a single day. A drift in energy as a function of BCU is shown. This implies that the energy decreases slightly from the beginning to end of a day about 1%. Results for BCU 11 and BCU 27 do not fall on the line are most likely due to a failure to insert the GAF Chromic film all the way into the holder (Ref Trevor Burris typical error). This has a very small effect on the calibration result since we are relying on the difference of the spectrometer result. BCU8 deviates from the BCU8 OFF line because it is operated at 20 kV instead of the nominal 25 kV.

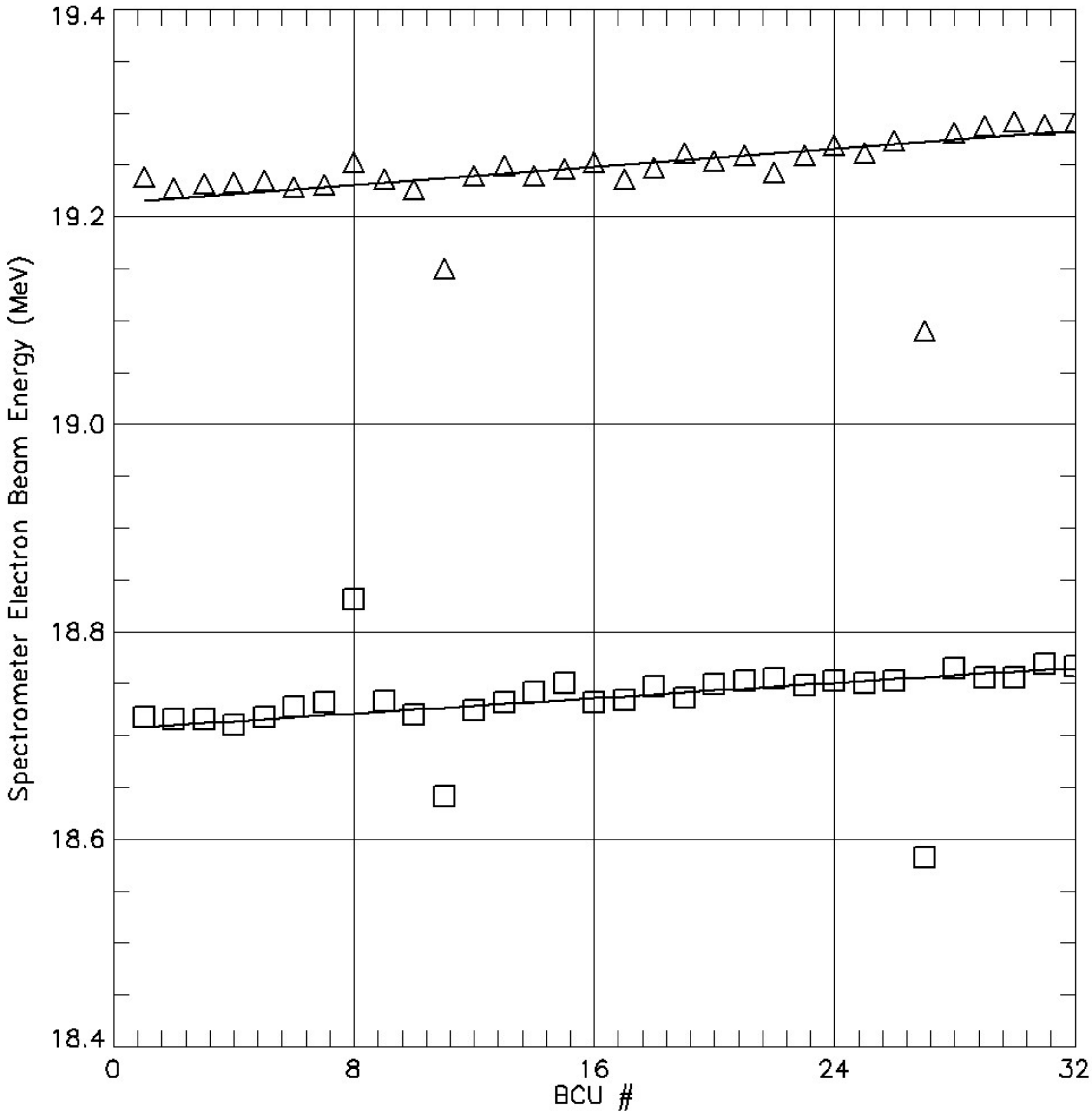


Figure 20. Energy for BCU ON and BCU OFF as a function of BCU number. Time of day starts at BCU32 and goes backwards.

References

1.) T. J. Burris-Mog, M. A. Chavez, M. A. Espy, M. J. Manard, D. C. Moir, J. B. Schillig[1], R. Trainham, *and* P. L. Volegov, Rev. Sci. Instrum. **89**, 073303 (2018), "Calibration of two compact permanent magnet spectrometers for high current electron linear induction accelerators"
2.) SABR Enterprises, LLC. (formerly Aster Enterprises), 6 Eastern Road, Acton, Massachusetts, USA, www.sabrllc.net.
3.) P W Allison, "xtr, A New Beam Dynamics Code for DARHT", DARHT Technical Note No. 50.